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of Engineers**

Waterways Experiment
Station

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CPAR-GL-97-2
July 1997

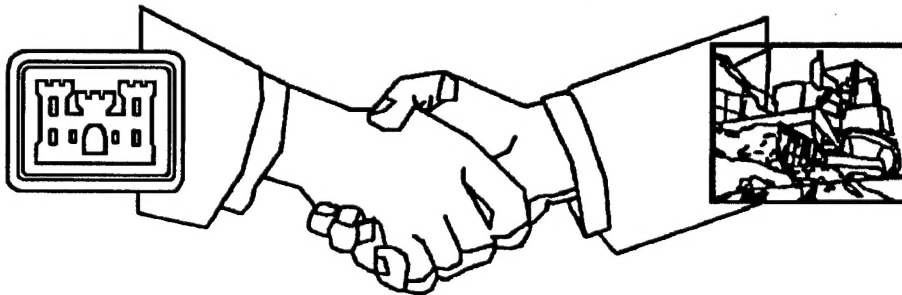
CONSTRUCTION PRODUCTIVITY ADVANCEMENT RESEARCH (CPAR) PROGRAM

**Monitoring Groundwater Levels Using
a Time-Domain Reflectometry (TDR) Pulser**

by

Glenn A. Nicholson, Jeff F. Powell, Kevin M. O'Connor

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**A Corps/Industry Partnership to Advance
Construction Productivity and Reduce Costs**

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Monitoring Groundwater Levels Using a Time-Domain Reflectometry (TDR) Pulser

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Final report

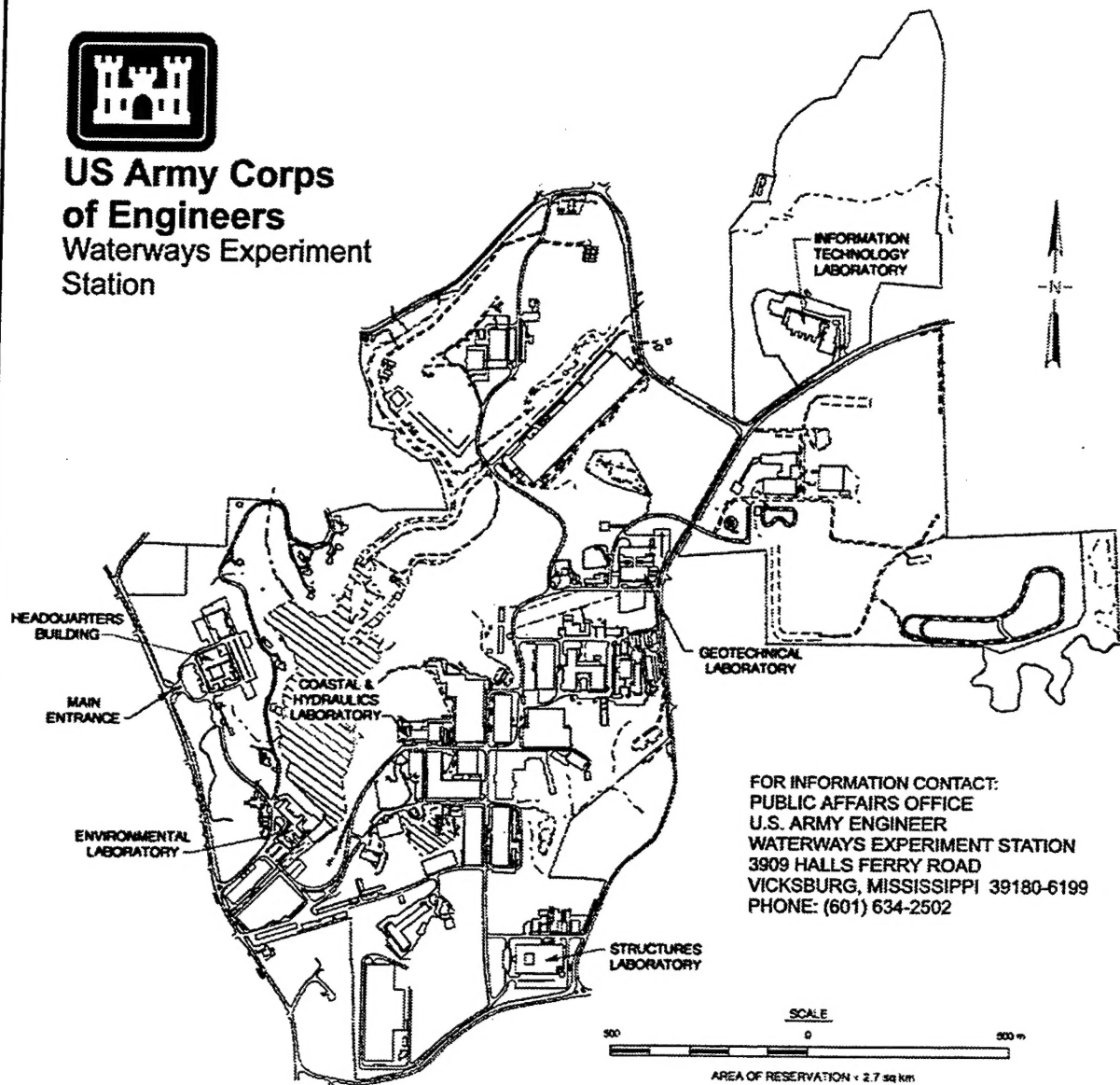
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**US Army Corps
of Engineers**
Waterways Experiment
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Preface

This study was conducted at the Geotechnical Laboratory (GL), U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, under the Construction Productivity Advancement Research (CPAR) Program. The study was begun in February 1995 and was completed in March 1997 under the project entitled "A Time-Domain Reflectometry (TDR) Pulser for Monitoring Groundwater Levels with Piezometers," Work Unit No. 33041. Headquarters, U.S. Army Corps of Engineers (HQUSACE), Technical Monitors were Messrs. Michael J. Klosterman (CECW-EC) and Dave Mathis (CERD-C). Mr. William F. McCleese was the WES CPAR Point of Contact.

The field testing and evaluation of the TDR monitoring system was conducted at WES by GL and Instrumentation Systems Development Division, Information Technology Laboratory (ITL), staff members. The Industry Partner was HYPERLABS, Inc., with Northwestern University Infrastructure Technology Institute (ITI) and the U.S. Department of Interior, Bureau of Mines (now abolished), Twin Cities Research Center (USBM-TCRC), as the Industry Participants. GeoTDR, Inc., provided technical assistance and advice. This report was prepared by Dr. Glenn A. Nicholson, GL; Mr. Jeff F. Powell, ITL, and Dr. Kevin M. O'Connor, GeoTDR, Inc. The project was under the general supervision of Drs. William F. Marcuson III, Director, GL; Don C. Banks, Chief, Soil and Rock Mechanics Division; and Mr. Jerry S. Huie, Chief, Rock Mechanics Branch. The authors wish to give special thanks to Dr. Charles H. Dowding, ITI, without whom the project would not have been possible. The authors would also like to thank Mrs. Mary Anne Kirklin and Mr. Bennie L. Washington, GL, for their assistance in preparing this report.

At the time this report was prepared, Dr. Robert W. Whalin was the Director of WES and COL Bruce K. Howard, EN, was Commander.

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Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	meters
inches	25.4	millimeters
kips (force)	4.448222	kilonewtons
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
pounds (force) per square inch	0.006894757	megapascals
¹ To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9) (F-32)$. To obtain kelvin (K) readings, use: $K = (5/9) (F-32) + 273.15$.		

1 Introduction

CPAR Program

The Congress, in enacting the Water Resources Development Act (WRDA) of 1988, authorized the U.S. Army Corps of Engineers (USACE) to enter its laboratories and research centers into, on a cost-shared basis, collaborative research/development with non-Federal entities. As a result of the WRDA authorization, the USACE initiated the Construction Productivity Advancement Research (CPAR) Program in 1989. The CPAR Program provided funding for USACE Laboratories (USACE-LABs) to enter into CPAR Cooperative Research and Development Agreements (CPAR-CRDA) with non-Federal corporations, sole proprietorships, trade associations, state and local governments, and colleges/universities, for the purpose of improving the productivity of the U.S. construction industry. USACE projects benefit from the use of CPAR technologies that result in improved construction productivity.

Background

The term "groundwater level" is defined as the elevation that the free water surface assumes in permeable soils or rock because of equilibrium with atmospheric pressure in a hole extending a short distance below the capillary zone. In strata that consist of alternating layers of permeable and impermeable soils and/or rock, any number of groundwater levels may exist.

The measurement of groundwater levels usually involves drilling a vertical hole and installing a pipe. Such pipes are referred to as either observation wells or piezometers. Observation wells do not incorporate subsurface seals that prevent a vertical connection between multiple strata and, hence, multiple groundwater levels. A piezometer is a measuring device (pipe) that is sealed within the ground so that it responds only to the groundwater level (pressure) around a predefined elevation. The pipe is generally perforated (e.g., slotted or screened) at the predefined elevation. Each observation well or piezometer is uniquely tailored to suit the needs of each site location.

The number of observation wells and piezometers currently installed at projects around the world is not known, but no doubt number in the

thousands. The number of observation wells and piezometers is likely to increase with the increased emphasis placed on the controlled disposal of waste materials and the need to provide continued monitoring to detect and prevent potential infusion of leachate plumes into the groundwater. In this respect, there are a number of different methods used to measure the distance from the top of the well or piezometer to the groundwater level. The simplest method consists of manually lowering the weighted end of a measuring tape until it touches the water. Another manual technique consists of lowering a pair of wires, uninsulated at their lower ends, until the circuit is completed as the wires contact the water surface (e.g., an M-scope). Hydraulic and pneumatic techniques are also available. However, the majority of long-term observation wells and piezometers are monitored with submerged electric transducers of either the vibrating wire or electrical resistance type. Piezometers and the monitoring of groundwater levels are discussed in great detail by Dunnicliff (1988) and in Engineer Manual 1110-2-1908, "Instrumentation of Embankment Dams and Levees" (Headquarters, Department of the Army (HQDA) 1995).

Submerged electric transducers are well suited for monitoring groundwater levels in that they are capable of detecting small changes in water levels and can be easily rigged with data loggers and telecommunication equipment for remote monitoring. However, as with any submerged electronic device, long-term protection against moisture penetration is difficult. Replacement of moisture damaged transducers is time-consuming and expensive. Transducers also require calibration and manual verification downhole that, while conceptually simple, often proves tedious in practice. Finally, transducers require relatively large riser pipes (usually 25-mm- (1.0 -in.-) ID, or larger).

Time-domain reflectometry (TDR) instruments are also capable of detecting small changes in water levels and can be outfitted for remote monitoring. With TDR instruments, a coaxial cable replaces the transducer, hence the electronics are fixed at the surface where they are accessible and easy to maintain. TDR installation is simple and does not require field calibration. Riser pipes as small as 12 mm (0.5 in.) may be used for installation. Finally, one TDR instrument can be multiplexed to monitor a number of wells/piezometers at the same time.

TDR technology had been successfully applied in measuring water levels in the laboratory prior to 1995. However, it was generally recognized that field application for monitoring groundwater levels required the development of a small rugged TDR pulsing device.

Objective

The objective of this CPAR-CRDA was to develop, demonstrate, and commercialize a rugged, self-calibrating, field instrument (referred to as TDR herein) for remotely monitoring groundwater levels/piezometer pressures. The key element of the instrument to be developed was a rugged,

miniaturized pulsing, signal recording, and discriminating device, which operates at low-power consumption in a harsh field environment.

Approach

The research, development, demonstration, and commercialization activities were divided into five phases: Phase 1 - Development of the preliminary design and specifications for the pulser; Phase 2 - Final design and fabrication of prototype to include laboratory proof testing; Phase 3 - Production of two commercial units; Phase 4 - Field installation, testing, and demonstration of the instrument; and Phase 5 - Commercialization and technology transfer. Phases 1, 2, 3, and 5 were primarily the responsibility of the Industry Partner. The U.S. Army Engineer Waterways Experiment Station (WES) assisted in the identification of critical field design parameters in Phase 1 and conducted the field installation and testing in Phase 4.

2 TDR Technology

Fundamentals

TDR technology is not new. The technology refers to techniques that emit short pulses of energy which are reflected to the source by some anomaly. The spatial location of the anomaly can be determined if the pulse velocity and pulse direction are known and the total pulse travel time is measured. Radar is an early example of TDR technology. As such, TDR technology used for monitoring groundwater elevations is essentially a closed-circuit radar in which a coaxial cable acts as a waveguide (i.e., the cable replaces the directional antenna). The technology was originally developed by the power and telecommunication industry to locate faults and breaks in transmission lines.

Coaxial cable TDR equipment, in its simplest form, consists of a pulse generator and a pulse sampler. The pulse generator emits a fast rise time (typically ranging between 10 to 10,000 pico seconds ($1.0 \text{ ps} - 10^{-12}$ seconds) depending on pulser) step pulse through the sampler and into the coaxial cable undergoing integration. Whenever there is a change in electrical properties along the cable, a portion of the voltage is reflected. The reflected pulse travels back through the cable to the sampler (e.g., an oscilloscope) and is identified upon arrival by a change in the interface voltage. A stable TDR waveform is developed by repeating this process many times. Andrews (1994) provides an excellent overview of coaxial cable TDR technology.

The TDR waveform consists of values of the reflection coefficient, which is the ratio of the reflected to the transmitted voltage and values of time or transmission distance. The waveform amplitude depends on the type of cable fault. The time delay between a transmitted pulse and the reflection from a cable fault uniquely determines the fault location. Travel time is converted to distance by knowing the propagation velocity which is a property of the cable. Furthermore, the time, sign, length, and amplitude of a reflection coefficient signature defines the location, type, and severity of cable fault. This principle has been adapted for monitoring water levels.

Water-Level Measurement with TDR

Fellner-Feldegg (1969) was perhaps the first to propose that the shape of the reflected TDR signature could be analyzed to define the low-frequency electrical conductivity. Furthermore, the shape of a reflected step pulse caused by a change in capacitance at an interface between air and a dielectric medium such as water was related to the change in dielectric constant. The characteristics of coaxial cable TDR not only allows the detection and location of water surface levels but also permits application to a wide variety of other areas such as measurement of soil moisture content, detection of hazardous materials, and monitoring deformations, to mention a few. The U.S. Department of Interior, Bureau of Mines (1994), provides an excellent collection of papers dealing with a wide variety of TDR applications.

Ross (1974, 1976) has patented several apparatuses and methods for the detection of liquid levels. He employed an open coaxial line immersed in a liquid which filled the open space between the inner and outer conductor. The liquid surface creates a change in capacitance which produces a reflection of the voltage pulse. In addition to coaxial cable, Ross used a single dielectric coated line (i.e., a Goubau line) coupled with a conducting container. Either of these sensor types can be used with a TDR unit.

Figure 1a shows a schematic of a piezometer equipped with a TDR pulser/sampler connected to a coaxial cable installed downhole. Figure 1b illustrates typical waveforms from reflect pulses for two water levels located at distances of H_1 to H_2 from the surface. Point a in Figure 1b signifies the entrance of the waveform into the top of the coaxial cable. The waveform remains constant until a negative (downward) reflection occurs at the air/water interface (water level 1, point b, Figure 1b) because of a change in capacitance (Dowding, Huang, and McComb 1996). The waveform again remains constant until the end of the cable is reached and a positive reflection occurs (point e, Figure 1b). Similar behavior is observed for the waveform representative of water level 2. The distance to the air/water interface (H) is determined from the total pulse travel time (TD) and the propagation velocity (V_p) (i.e., $H = (TD)(V_p)/2$). It is interesting to note that from the waveform the cable appears longer when the water level is at H_1 . This apparent discrepancy is caused by the fact that the total submerged travel distance to the end of the cable is greater when the water level is at H_1 than when at H_2 . The cable appears longer because the pulse propagation velocity in water is less than the propagation velocity in air (i.e., $V_p(\text{water}) = (1/81) V_p(\text{air})$).

The majority of TDR equipment currently in use incorporates a pulser and a feed-thru oscilloscope into a single unit. The oscilloscope allows visual examination of the total waveform. The negative waveform inflection signifying the air/water interface is usually visually selected by the operator. Since the distance to the water level is the product of travel time and a constant (i.e., the propagation velocity), the distances H_1 , H_2 , and ΔH can be scaled directly from the oscilloscope screen.

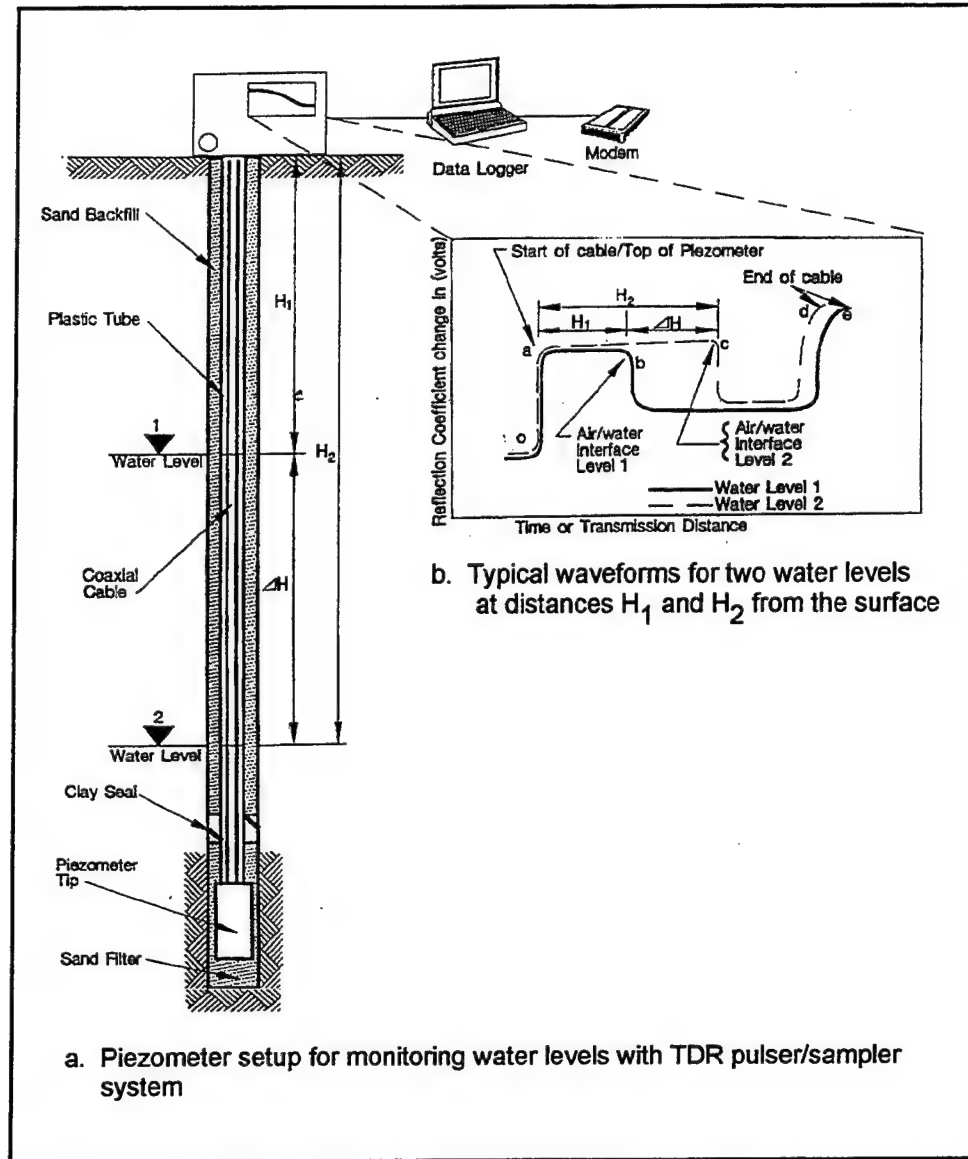


Figure 1. Schematic of TDR pulser sampler

Cables

McComb (1992) demonstrated that the air/water interface can be detected with a parallel wire configuration other than coaxial cable. The parallel or two-wire approach (e.g., TV antenna wire) proved to be particularly attractive for very small-diameter (i.e., less than 12-mm ID) riser pipes. However, McComb found that the coaxial cable configuration provided a much sharper and more distinct negative reflection at the air/water interface than did the TV wire configuration.

Coaxial cables are manufactured in a number of configurations. The coaxial cable that appears to work best with TDR technology consists of an

inner conductor that is separated from a solid metallic outer conductor by a plastic spiral separator. Although a significant proportion of the volume between the inner and outer conductors is filled with air, they are frequently referred to as "spiral filled" coaxial cables. The cables are manufactured in a variety of conductor material combinations such as aluminum/copper or copper/copper. The commonly used combination consists of an aluminum outer conductor and a copper-plated aluminum inner conductor. The solid outer conductor provides sufficient stiffness to allow easy insertion into riser pipes without curling or kinking.

Cable Enhancement

Distortion of the coaxial cable, in the form of crimps, causes a change in capacitance and generates a negative reflection spike in the TDR waveform. Dowding and Huang (1994a) have employed cable crimps spaced at regular distances down the length of long coaxial cables deployed to measure rock mass shearing. The crimps serve as fixed distance markers to improve the accuracy of distance measurements. Crimps would serve equally well where long cables are used to monitor groundwater levels.

Dowding and Huang (1994b) suggest that small holes drilled through the outer metal conductor will facilitate the rise of water into the air space between the inner and outer conductors. Drill holes would also allow water to drain rapidly from the cable in the event of a rapid drawdown of well water.

Complementary Technology

Rapid and efficient methods have been developed for setting temporary monitoring wells (Shinn and Bratton 1995). Four routine temporary well installations, 38-mm- (1.5-in.-) ID Schedule 40 PVC pipe, are installed using a cone penetration test (CPT) rig. A steel sacrificial well tip is threaded onto a cleaned, slotted PVC section that may contain a filter pack. This tip section is then threaded onto a 1-m (3-ft) section of PVC riser. This composite section is lowered through a head clamp and guide tube to the ground surface. The 36-mm- (1.4-in.-) OD CPT push rods are then lowered into the center of the PVC sections and seated against the steel push point. The head clamp is used to grip the CPT push rods and push the PVC sections into the ground. To advance the well until the desired depth has been reached, 1-m (3-ft) sections of PVC riser material and CPT push rods are added sequentially. Once the final depth has been reached, the inner CPT push rods are retracted, leaving an installed well.

In cases where it is desired to grout PVC wells in place, a modification of the above installation technique is used. For this procedure, a 76-mm (3-in.) oversized point is attached to a 60.0-cm (2-ft) section of 76-mm (3-in.) slotted steel well casing. A 38-mm (1.5-in.) ID slotted PVC section is inserted

inside the steel casing, and a sand pack is placed between the two members. The sand pack is followed by a 15.0-cm (6-in.) section of bentonite granules to seal in the sand pack. Approximately 30.0 cm (1 ft) above the bentonite, a steel ground injection port is clamped to the PVC riser pipes. This entire point assembly is pushed up into the guide tube and 1-m (3-ft) sections of 38-mm- (1.5-in.-) inside diameter PVC risers are attached. The entire assembly is inserted and pushed to the final depth using the CPT push rods. During the pushing cycles, grout is pumped through a hose to the injection port. This immediately fills the annulus created by the oversized well tip with grout eliminating the possibility of the soil pinching off the annulus and creating an ungrouted zone. Disadvantages of this installation method are that it cannot be pushed to as great depths as other methods, and it is slower.

For very deep well installations, a method has developed for installing 12-mm- (0.5-in.-) OD flush-coupled PVC pipe fitted with a slotted sampling section. A disposable tip is pushed down to the desired sampling depth by 45-mm- (1.75-in.-) diam push rods. Attached to the tip is a PVC well screen. This well screen and additional riser sections are protected during the penetration by the CPT push rods. Once the desired depth has been obtained, the push rods are retracted, leaving the PVC well in place.

3 TDR Equipment

Pulser/Controller

The key element of the TDR instrument developed under this CPAR agreement consisted of a rugged, miniaturized pulsing and sampling device which operates at low-power consumption. The device is marketed and sold by HYPERLABS, Inc., Beaverton, OR, as the HL 1500 Assembled TDR System. As packaged and shown in Figure 2, the dimensions of the assembled unit measure $21 \times 11 \times 5$ cm ($8.25 \times 9.3 \times 2.0$ in.). The pulser emits a step pulse with a 200-ps rise time and 12.2-ps time-steps. Power consumption is less than 1 watt and operates from a 12-volt (nominal) DC battery.

The HL 1500 unit consists of a controller board and a TDR pulser card. The controller board contains communication software installed on a permanent read-only memory (PROM) chip with an RS 232 interface. To communicate with the unit, it is necessary to run a terminal emulation program on a personal computer (e.g., a laptop or hand-held) installed with Microsoft Windows. Alternatively, data may be collected and stored in a data logger and then downloaded to a personal computer at the user's convenience. A cellular or hardwired telecommunications interface can be used for remote communication.

The type and quality of cables and cable connectors used downhole for water-level monitoring as well as between the pulsing unit and the well head is important. Impedance mismatches and poor coupling between cable connectors can cause variations in pulse propagation velocity, signal losses, and erroneous cable fault reflections. For these reasons, it is essential that all cables and cable connectors be of high quality and in good repair. Optimum performance with the HL 1500 unit is achieved with 50-ohm spiral-filled coaxial cables with metal (i.e., aluminum/aluminum or aluminum/copper) conductors.

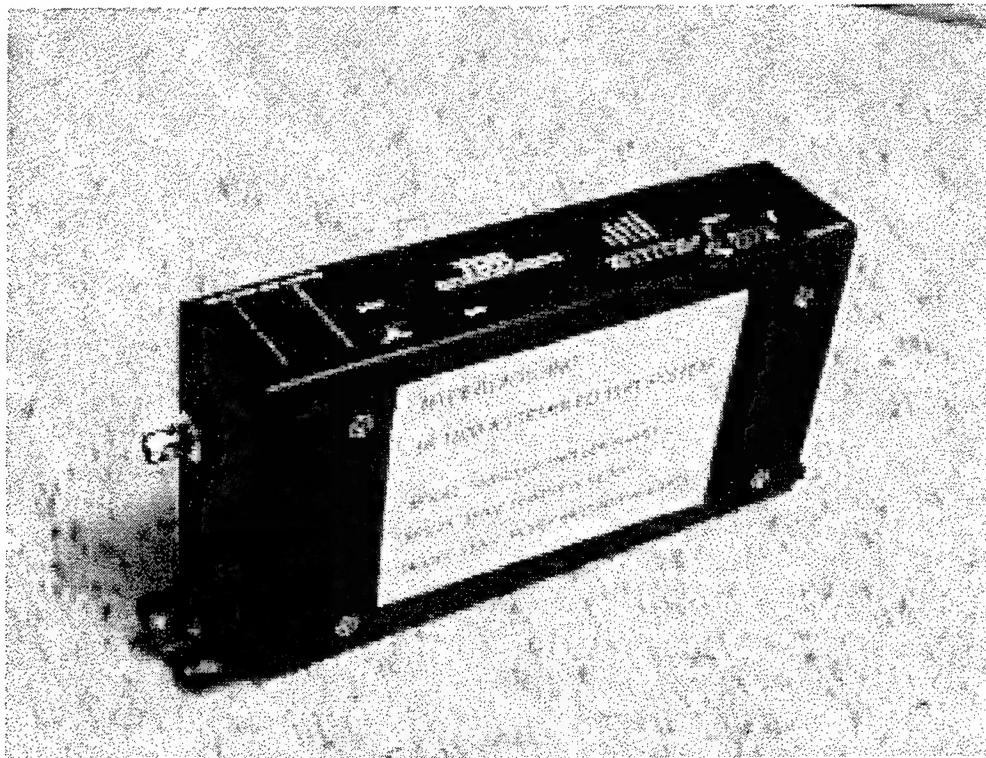


Figure 2. The HYPERLABS, Inc., HL 1500 assembled TDR system

Basic Operations

Water-level elevations may be obtained either as a direct readout or by visually analyzing the waveform as implied in Figure 1b. Both techniques require communication with the HL 1500 through a PC with a Terminal Emulator program. Once communication is established, the Main Menu is accessed as shown in Table 1. For a direct readout of water-level elevation, only two commands listed on the Menu are of primary interest, Set Reference Length (SRL) and Get Liquid Level (GLL).

Table 1
HL 1500 Main Menu

HELP [command name] gets help on a specific command	
SNP	Set Number of Points
SNA	Set Number Ave
SVP	Set Vp
SCV	Set Cal. Voltage
SDI	Set Distance
GWA	Get Waveform
SRL	Set Reference Length
DUMP (D)	Dump all setup parameters
>	

The SRL command establishes the length of lead cable often used to connect the HL 1500 to the downhole monitoring cable at the top of the well. Use of a lead cable allows the HL 1500 to be centrally placed for multiplexing so that a number of wells can be monitored. To set the reference length, a short circuit is made between the inner and outer conductors of the lead cable and the SRL command executed. The short circuit causes a pronounced negative reflection that is detected/recorded by the controller.

The GLL command activates a routine within the controller that searches for a large negative reflection from the air/water interface. The controller recognizes a negative reflection as the air/water interface only if the amplitude of reflected wave is equal to or greater than 75 percent of initial wave amplitude (i.e., 75 percent of the change in voltage from point 0 to point a in Figure 1b). If such a reflection is detected, the distance to the liquid level is displayed as "Distance to Liquid Level (meters) = (a value with 3 decimal places)." The distance to the liquid level displayed is the distance from the top of the downhole monitoring cable to the air/water interface. In essence, the controller calculates the total distance from the HL 1500 to the air/water interface (as defined by the large negative reflection) and subtracts the length of the lead cable as determined by the SRL command.

Because not all large negative reflections signify an air/water interface, it is sometimes advantageous to visually examine the TDR waveform. Visual examination of the waveform allows location and identification of cable faults (e.g., poor cable connections) that is sometimes necessary for debugging during system installation. Acquisition of the waveform also makes it possible to monitor system performance by examining the quality of the waveform. For the prototype HL 1500 (i.e., one of two initial production prototypes), the waveform was accessed through a Hardware Test (HT) command. In essence, the controller captures and stores the waveform data. The data are retrieved and stored in a PC through a terminal emulation program as an ASCII file of two columns. The first column consists of a series of data point numbers from 0 to 1023 (i.e., 1024 data points). The data point numbers represent equal time-steps (i.e., equated to equal distance) at which relative reflected wave voltage changes are measured. To generate a waveform plot, the data must be manipulated and plotted.

Several types of programs are commercially available for manipulating and plotting which include: TDR Reflection Analysis Program (TRAP) marketed by GeoTDR, Inc., and WIN TDR sold by Utah State University. However, with commercial production of the HL 1500, HYPERLABS, Inc., plans to provide a software package that will automatically retrieve and display the waveform as a function of the reflection coefficient and transmission distance similar to the form illustrated in Figure 1b. The HYPERLABS software package eliminates all of the detailed steps necessary for generating the waveform with the prototype unit. For this reason, the generation of waveforms will not be discussed in further detail. Instead, potential customers should contact HYPERLABS, Inc., for complete details.

In addition to waveform retrieval, several other commands are of importance. When the Dump (D) command (Dump all setup parameters) from the

Main Menu is invoked, the menu shown in Table 2 is accessed. Of the 11 parameters listed in Table 2, only 4 can be modified by a user: propagation velocity (Vp); number of waveforms averaged (Ave); number of data points per window (Points); and distance where windows begins (Distance). Of these four parameters only the Vp parameter will be discussed. The other three parameters Ave, Points, and Distance were used in the prototype HL 1500 for waveform retrieval and therefore will not be discussed.

Table 2
Menu for Setup Parameters

>d	
ROM Version =	1.080
VP =	0.920
Ave =	8.000
Points =	250.000
Distance =	1.000
Window =	0.500
Probe Length =	3.000
Probe Offset =	0.000
Cal. Voltage =	0.000
Cable Ref. =	-0.000
Time Resol. =	0.001

The Propagation Velocity (Vp) is by default set at 0.920. In essence, 0.920 represents a correction factor applied to the speed of light constant (C) where $C = 3 \times 10^8$ m/sec. Hence, in the case of the default setting $V_p = 0.920 \times 3 \times 10^8$ m/sec or $V_p = 2.76 \times 10^8$ m/sec. It should be noted that 2.76×10^8 m/sec is the average propagation velocity of the TDR pulse as it travels through typical 1.0 cm (3/8-in.-) OD spiral-filled coaxial cable. The HL 1500 controller uses this value to calculate the pulse travel distance in determining the liquid-level elevation.

The correction factor for any cable used can be determined simply by setting Vp to 1.000, pulsing a known length of the cable for which a short circuit has been made at the end of the cable, and invoking the GLL command. The controller will interpret the short circuit as a liquid level and calculate the distance to the end of the cable. The corrected Vp correction factor value is the ratio of the calculated length and the actual length.

Temperature Tolerance

As stated in the CPAR agreement, the objective was to develop, demonstrate, and commercialize a *rugged*, self-calibrating, field instrument. For a field instrument to be rugged, it must be operationally functional over a wide range of environments and associated temperatures. For this reason, HYPERLABS, Inc., conducted a temperature tolerance test on the prototype HL 1500 unit.

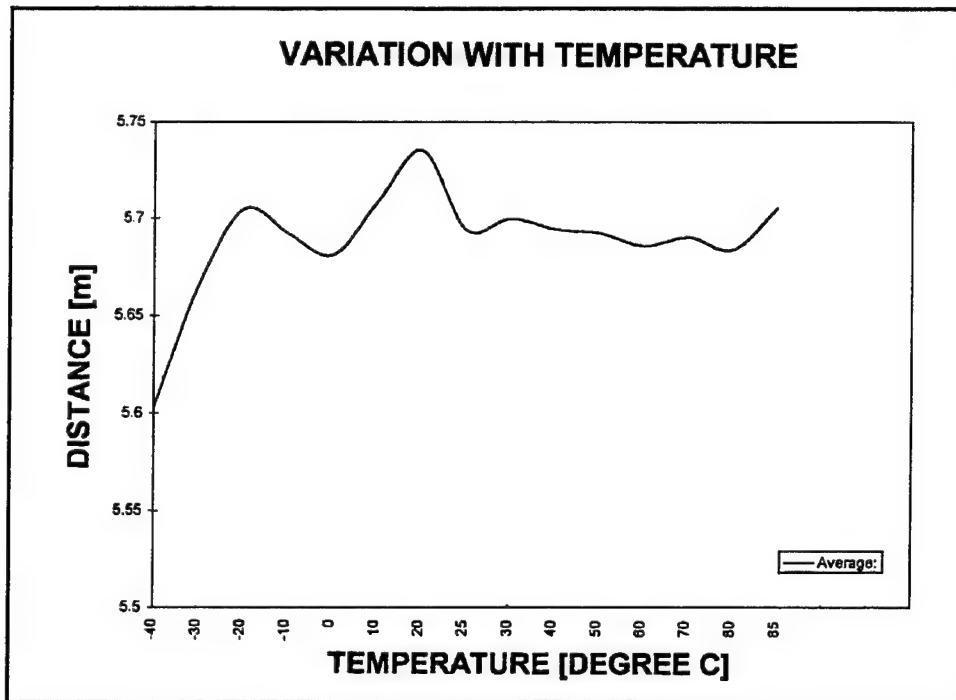


Figure 3. Plot of average water-level readings versus temperature

In this respect, the HL 1500 was placed in a temperature controlled chamber and connected to a 1.0-cm- (3/8-in.-) OD spiral-filled coaxial cable with a length of approximately 6.0 m (20 ft). The cable end was submerged in a beaker of water. The distance between the HL 1500 and the air/water interface was held constant. The initial chamber temperature was set at -40°C and held constant until the HL 1500 temperature reached equilibrium with the chamber. A total of 10 water level measurements were made using the GLL command. The process was repeated at $+10^{\circ}\text{C}$ increments up to 80°C . Additional water-level measurements were made at 25 and 85°C . The test results are listed in Appendix A. Figure 3 shows a plot of average water-level readings and the range of temperatures. Figure 3 indicates that over the total range of temperatures (i.e., -40°C to $+85^{\circ}\text{C}$), average measurements range from 5.604 m (18.386 ft) at -40°C to 5.736 m (18.819 ft) at $+20^{\circ}\text{C}$ for a maximum average variation of 13.2 cm (5.2 in.). However, if readings from -20°C to $+85^{\circ}\text{C}$ are considered the maximum, average variation is only 4.3 cm (1.7 in.).

Variability Tests

HYPERLABS, Inc., also conducted a series of tests to define the typical variability that might be expected from a number of water-level readings made with the HL 1500. Toward this end, the HL 1500 was connected to a 1.0-cm- (3/8-in.-OD) spiral-filled coaxial cable approximately 6.0 m (20 ft) in length. As in the temperature tests, the end of the cable was submerged in water and the water level held constant. A series of 10 water-level readings

were made every 1 to 2 hrs over a 24-hr period. The test data and results are listed in Appendix A. A plot of the average measured distance to the air/water interface versus time of day is shown in Figure 4. As can be seen from Figure 4, the distance to the liquid-level readings ranged from 5.868 m to 5.849 m (19.252 to 19.190 ft) for a maximum spread of 1.9 cm (0.75 in.). The standard deviation for all readings was 0.54 cm (0.21 in.).

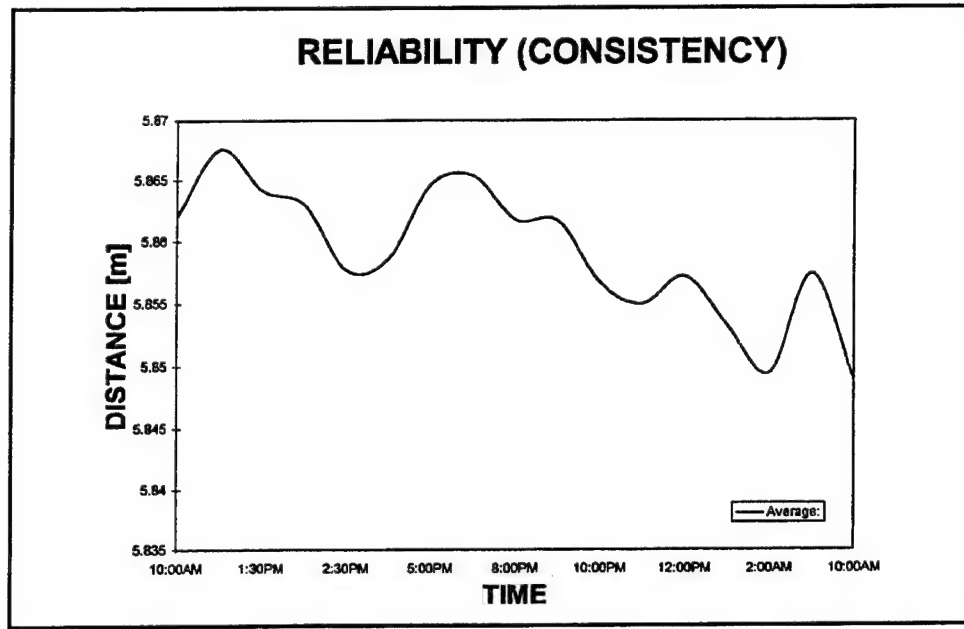


Figure 4. Plot of average water-level readings versus time of day

4 Field Evaluation

General

Field instrumentation must perform its intended function over extended periods of time and often in extreme environmental conditions. In this respect, WES' primary task under the CPAR-CRDA agreement was to evaluate the HL 1500 under field conditions. Initially, WES planned to install the TDR device at a site subject to harsh seasonal changes. As such, groundwater elevations at the chosen site would be monitored remotely. However, the initial plan was discarded early in the program because of travel costs that could occur in maintaining prototype equipment. For this reason, a suitable site located at WES was selected for evaluating the HL 1500. A WES site would also be advantageous for a demonstration workshop.

Well Selected for Monitoring

The well selected for monitoring is located adjacent to the parking lot in front of the WES Geotechnical Laboratory (i.e., the Arthur Casagrande Building). The well was developed in 1985 and dedicated for the purpose of testing and demonstrating downhole geophysical logging equipment. The well extends to a depth of 92 m (301 ft). The top 40 m (133 ft) of overburden, consisting of lean sandy clays with an occasional lens of fat inorganic clay, was cased in a 10.0-cm (4.0-in.) schedule 80 PVC pipe. The casing terminated at the top of the Glendon Limestone Formation. The well head consisted of a 20-cm- (8-in.-) diam by 2.8-m- (9.3-ft-) long steel collar pipe. The well drilling logs are provided in Appendix B. For the period monitored, groundwater elevation ranged from approximately 95- to 93-m (312- to 305-ft) mean sea level or approximately 7 to 5 m (23 to 16 ft) below the top of the well head.

System Components

Figure 5 shows a block diagram for the remotely operated TDR system used to measure the water-level depth in the well. The system may be operated at the well or from a remote location by simply placing a call to the TDR system utilizing a personal computer and a modem. The components mounted at the well site can be divided into two subsystems. These include the power subsystem and the data acquisition subsystem.

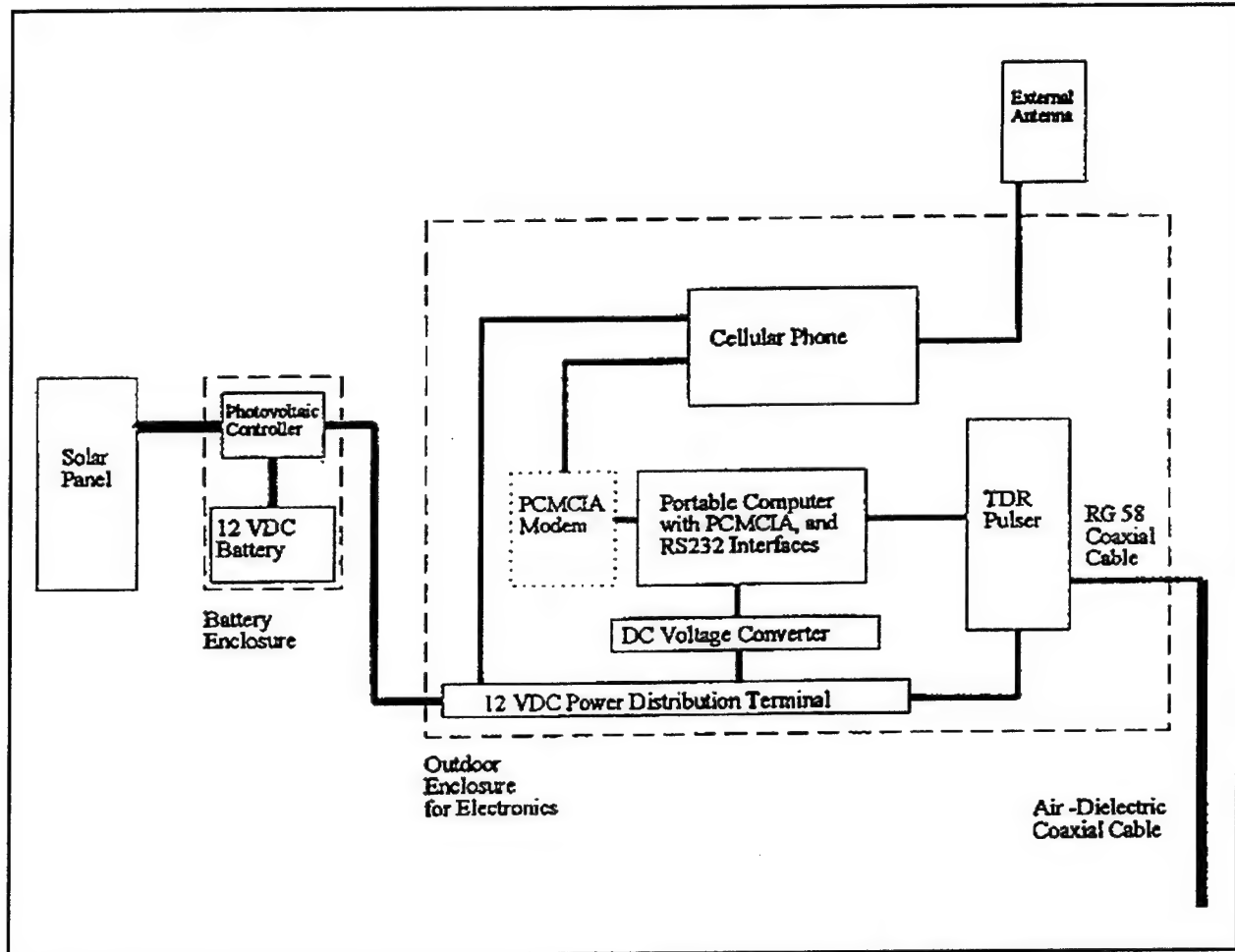


Figure 5. Block diagram for a remotely operated TDR monitoring system

The power subsystem, shown in Figure 6, consists of a deep-cycle marine battery operating at 12 volts DC with an approximate capacity of 100 amp hours. A solar panel is used to keep the battery charged. A solar panel with a maximum output voltage of 17 volts DC and a corresponding output current of approximately 4.4 amps provides a panel with an approximate maximum rating of 75 watts, depending on available sunlight. Flexible conduit is used to connect the output of the solar panel to the battery enclosure. A photovoltaic controller regulates charging of the battery to provide a constant

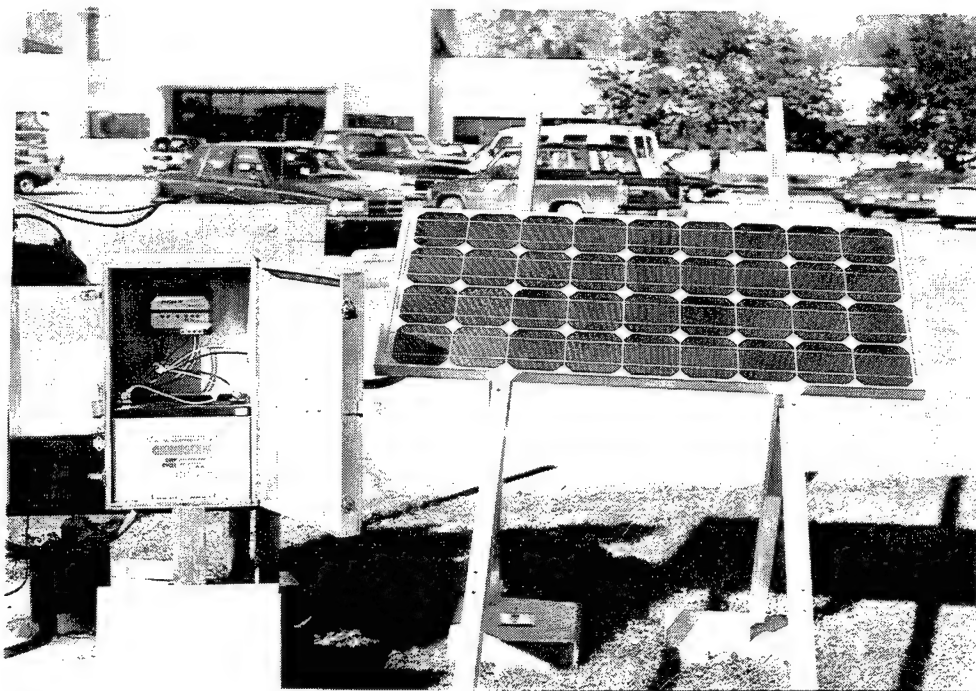


Figure 6. Photograph of the power subsystem

12-volt DC output for the data acquisition system. This output to the data acquisition system is provided via flexible conduit from the battery enclosure to the electronics enclosure. Power is then distributed to the major components in the data acquisition system from a centrally located power distribution terminal strip located in the electronics enclosure.

The data acquisition subsystem, shown in Figure 7, is made up of three major components. These components include the TDR pulser with appropriate cable, a portable computer with a modem and a RS-232 interface, and a cellular phone system. All components are enclosed in a NEMA rated outdoor enclosure. An air-dielectric coaxial cable is mounted in place, down the well of interest. The TDR pulser, which is the heart of the measurement system, attaches to the air-dielectric cable using a relatively short length of RG 58 coaxial cable. Cables are connected using appropriate BNC and N-type connectors.

The operator can communicate with the TDR pulser by using a portable computer with a serial cable attached from the computer's RS-232 port to the pulser's RS-232 port. A terminal emulation program installed on the computer is set up to communicate with the TDR pulser, according to appropriate communication parameters. A cellular phone system, along with software, is used to communicate and operate the TDR pulser from a remote location. To accomplish this, the portable computer must have a modem installed in one of its PCMCIA slots. A cellular phone system is connected to the portable computer modem by a special interface technology. This special interface provides a bridge between standard land-based phone equipment and cellular transceivers. This interface allows the user to connect the RJ11 plug from the modem directly into the cellular telephone system and operate it as

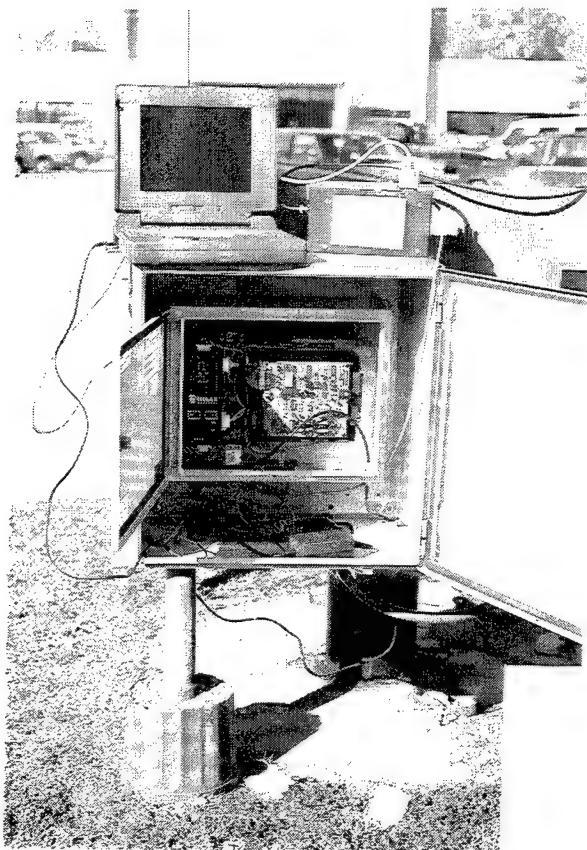


Figure 7. Photograph of data acquisition subsystem

cable approximately 1.5 m (5.0 ft) long was connected to the HL 1500 and the “set reference length” operation was performed. Finally, the lead cable was connected to the downhole 1.0-cm (3/8-in.) coaxial cable using BNC and N-type connectors.

if it were a land-based system. Lastly, an antenna was required for the cellular phone system.

Installation

Equipment installation on 2 April 1996 was simple. Once the necessary all-weather outdoor equipment enclosures were in place, the entire installation required less than 15 min. In essence, 1.0-cm (3/8-in.) coaxial cable of sufficient length (in this case 12 m (40 ft)) was stretched out on a flat surface (Figure 8). A clamp was attached to the surface end of the cable to hold the cable in place at the well head. To keep the cable straight, a 4.5-kg (10-lb) weight was attached to the cable bottom. The cable plus weight were then lowered into the well (Figure 9). A lead cable consisting of RG 58 coaxial

Monitoring

The monitoring of groundwater levels began immediately after installation of the HL 1500 pulser and the down-well coaxial cable. As a rule, readings were taken twice a day (morning and afternoon) for the first week; then twice a week for the next 2 weeks, after which readings were made more or less once a week. As a rule, the instrument was inspected once a day, even on days when no readings were recorded, to ensure that the equipment was functional. A reading consisted of at least three executions of the “GLL” command with each execution spaced 2 to 3 min apart. The “get liquid level” value displayed on the monitor was recorded, and the elevation of the groundwater was calculated. The depth to the groundwater level was also



Figure 8. Photograph of 1.0-cm (3/8-in.) coaxial cabled ready to be lowered into the well

manually measured with an M-scope each time a set of readings was made. M-scope measurements were converted to groundwater elevations. The TDR HL 1500 and M-scope readings data are given in Appendix C. The data list the day the reading was made, the highest and the lowest elevation observed that day from TDR readings, the total spread or range of TDR elevations, and the average TDR elevation. The groundwater elevation obtained from M-scope measurements are also listed along with the difference between the average TDR elevation and the M-scope elevations. Figure 10 shows a plot of both the average daily TDR obtained elevations and M-scope obtained elevations versus days.

An examination of Figure 10 indicates at least two important observations. First, there is remarkably good agreement between the groundwater elevation determined from TDR HL 1500 and the M-scope. Second, it is interesting to note that except for the last two readings, the M-scope reading was slightly higher (average 0.33 cm (1.30 in.)) (Table C1) than the TDR reading. For reasons explained below, the reverse is true for the last two readings. From a practical view, the slight differences in the two elevation readings are insignificant. It should be noted that the propagation velocity (V_p term in Table 1) was preset by HYPERLABS and, as such, represents an average velocity for the general type of coaxial cable used in this study. Greater agreement could have been realized by adjusting the " V_p " parameter upon installation.

An indication of equipment readout variability that might be expected in field applications can be obtained from Table C1. The difference between the highest and lowest reading on a given day (i.e., spread in Table C1) ranged from 9.5 cm to 0.2 cm (3.74 in. to 0.08 in.) for an average of 1.7 cm (0.67 in.). On the average, under field conditions, the spread in readings obtained from the HL 1500 varied by plus or minus 0.85 cm (0.33 in.). Plus or minus 0.85 cm (0.33 in.) compares favorably with an average standard deviation of 0.54 cm (0.21 in.) reported by HYPERLABS in Table 2a.



Figure 9. Photograph of 1.0-cm (3/8-in.) diam coaxial cable being lowered into the well

Although not specifically stated, the discussions imply that the M-scope measurements were intended as a datum reference or ground truth. In this respect, it is only fair to examine the possible precision of the device. The units of measure for the M-scope used in this study were feet, tenths of a foot, and two-hundredths of a foot. In other words, the level of precision for any given reading was, from a practical standpoint, no closer than plus or minus 0.01 ft or, converting to metric units, plus or minus 0.305 cm.

For completeness of discussion an explanation should be given as to why the differences between the average TDR and M-scope readings (see Figure 10 and Table C1) changed from a negative to a positive value.

The initial CPAR agreement required the manufacture of two prototype HL 1500s during the first year of the research effort. One of the prototypes was sent to WES for field testing. As initially designed and delivered, the primary function of the HL 1500 was to serve as an intelligent box that pulsed the coaxial cable, analyzed the reflected waveform, and calculated the distance to the first large negative reflection source. This calculated distance was displayed on the PC monitor as the distance to the liquid level. The HL 1500 performed this intended task in a flawless manner. The HL 1500 also contained provisions for accessing waveform data that could, with proper processing, result in waveform plots. However, this initial waveform retrieval process was, at best, tedious. Although not part of the initial CPAR agreement, after several months of field testing and becoming familiar with the HL 1500's potential capabilities, all parties involved in the study came to realize that a more user-friendly procedure for retrieving waveforms was needed. Approximately mid-July 1996, the prototype HL 1500 was returned to HYPERLABS for upgrading the controller card to allow easier retrieval of the waveforms and so that HYPERLABS could perform temperature and repeatability tests. In the process of upgrading the controller card, HYPERLABS slightly decreased the value for the propagation velocity coefficient.

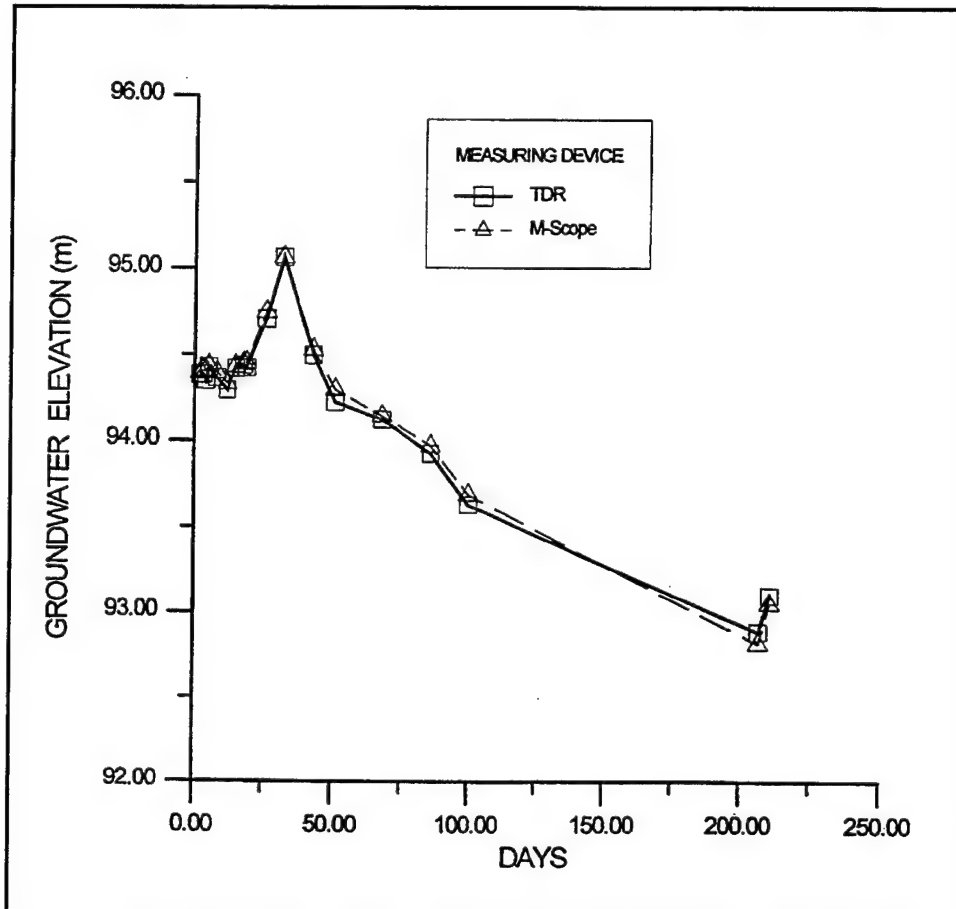


Figure 10. Plot of average daily TDR and M-scope elevation readings versus days after installation

Hence, when the instrument was put back into service toward the end of October 1996, the TDR readings resulted in elevation values slightly lower than the M-scope values.

5 Conclusions and Recommendations

Summary of Capabilities

To restate, the objective of this CPAR agreement was to develop, demonstrate, and commercialize a rugged self-calibrating field instrument (referred to as a TDR herein) for remotely monitoring groundwater levels/piezometer pressures. The key element of the TDR device (HL 1500) is a rugged miniaturized pulsing and signal recording and discriminating device, which operates at low-power consumption in a harsh field environment. As measured against the overall objective, the research effort was a complete success. The HL 1500 consists of a small, 21- × 11- × 5-cm (8.25- × 4.3- × 2.0-in.) pulser/controller capable of pulsing a coaxial cable (partly submerged in water). The HL 1500 then detects, captures, and analyzes the reflected pulse and calculates the distance to the air/water interface. It is rugged as evidenced by successful field evaluation with zero problems over a 215-day period. Temperatures over the 215 days ranged from 2°C (35°F) to 37°C (98°F) with relative humidities of up to 100 percent. In laboratory temperature tests, the HL 1500 was operational at temperatures ranging from -40°C (-40°F) to 85°C (185°F). In operation, the device consumes less than 1 watt of power. Additional capabilities and attributes are summarized below.

- a.* The HL 1500, along with the necessary coaxial cable and personal computer or data logger, is easy to install. Installation required less than 15 min for the 12 m (40 ft) of coaxial cable, the HL 1500, and the laptop PC used at WES.
- b.* The system is adaptable to cellular or regular hardwire phone systems (requires special interface between phone and PC monitor) for remote monitoring. Remote monitoring requires provisions for maintaining a DC power supply. However, while the basic system (i.e., HL 1500, coaxial cable, and PC) can be easily installed by an individual with only a casual knowledge of instrumentation, installation with remote monitoring capabilities requires the expertise of personnel experienced in installation of electronic instrumentation.

- c. The HL 1500 system is self-calibrating. The system interprets the first large negative reflection as the air/water interface. However, the user must be aware that other factors (e.g., a short circuit between the inner and outer conductors) will also cause a large negative reflection that could be interpreted as the air/water interface. In this respect, the user should verify (through manual measurement with an M-scope or similar device) the initial TDR water-level reading.
- d. Both laboratory reliability tests and field evaluation indicate that the expected variability in readings is approximately plus or minus 0.5 cm (0.20 in.) about the mean. In terms of practical significance, 0.5-cm (0.2-in.) variability in piezometric head translates into plus or minus 50 Pa (0.007 psi). In this respect, the HL 1500 more than satisfies the level of precision required for typical geotechnical applications. However, it must be noted that the issue of precision (i.e., variability) was examined for relatively shallow water levels ranging from 5 to 7 m (16 to 23 ft) from the top of the coaxial cable. Precision is likely to decrease slightly (increase in reading variations) with significant increases in water depths.

Conclusions

Field evaluation at WES indicates that the HL 1500 performs as envisioned by the initial CPAR objective. The basic TDR system to include the HL 1500, appropriate coaxial cable and personal computer or data logger possesses unique advantages over conventional downhole electric transducers. That is, with the TDR system all the electronics are located at the surface where they can be easily maintained. Since only the coaxial cable is installed downhole, piezometer riser pipes as small as 12-mm (0.5-in.) ID can be used. With the proper interfaces, the basic system is compatible with a wide variety of peripheral hardware features such as telecommunication for remote monitoring and multiplexing for monitoring a number of wells with a single system. The technology is compatible with current data acquisition devices in use by the Corps and does not require additional equipment, personnel, or special training. In summary, TDR provides a viable alternative for monitoring groundwater/piezometric levels in the field while providing significant reductions in maintenance costs. The device is recommended for general use in monitoring groundwater levels/piezometric pressures.

6 Commercialization and Technology Transfer

HL 1500 Commercial Availability

HYPERLABS, Inc., is the principal developer of the HL 1500. Certain components, primarily the controller board, are the property of Campbell Scientific, Inc., Logan, UT. Campbell Scientific also manufactures circuit boards for the HL 1500. As such, HYPERLABS, Inc., markets the HL 1500 independently and through an original equipment manufacturer's agreement with Campbell Scientific. Sales and technical services for the HL 1500 can be obtained from:

HYPERLABS, Inc.
13830 SW Rawhide Ct.
Beaverton, OR 97005

The HL 1500 sells for approximately \$3,000.00 in 1997 dollars. As of the writing of this report, the \$3,000.00 purchase price included the user-friendly software package for accessing and displaying the complete waveform. The waveform package allows the user to identify and locate problems associated with poor cable connectors and other cable fault problems that would otherwise require trial-and-error elimination. In this respect, the waveform package provides a vital debugging tool. It should be noted, however, that the waveform software is likely to undergo further development in the future, and as such, any additional cost that might be incurred would be passed on to the consumer.

HYPERLABS, Inc., recommends that a high-quality 50-ohm "spiral filled" coaxial cable, 9.5 mm (3/8 in.) in diameter, be used as the down-well cable. A number of companies manufacture suitable cables with costs ranging from \$6.00 to \$13.00 per m (\$2.50 to \$4.00 per ft).

Technology Transfer

The Industry Partner (HYPERLABS, Inc.) and Participant, (Infrastructure Technology Institute (ITI) at Northwestern University), as well as WES, have published the results of this research at both an international symposium and technical journal (Dowding et al. (1996) and Dowding, Huang, and McComb 1996). In November, a workshop was held at WES to demonstrate the TDR system. The workshop was attended by individuals from private industry, academia, and the Corps of Engineers. At the present, the Industry Partner plans to actively display/demonstrate the system at national geotechnical conferences.

The TDR technology is compatible with current monitoring systems and, as such, requires no changes in any existing Corps of Engineers policy or guidance manuals.

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Appendix A

HYPERLABS' Temperature and Reliability Test Results

Table A1 HYPERLABS: Temperature Test Results																			
Temperature		Temperature Test (Distance to Water Lever in Meters)																	
C	-40	-30	-20	-10	0	10	20	25	30	40	50	60	70	80	85				
F	-40	-22	-4	14	32	50	68	77	86	104	122	140	158	176	185				
Measurement																			
1	5.629	5.707	5.691	5.683	5.673	5.711	5.706	5.696	5.687	5.693	5.686	5.685	5.693	5.682	5.688				
2	5.608	5.669	5.706	5.691	5.684	5.72	5.737	5.686	5.713	5.712	5.695	5.671	5.691	5.687	5.696				
3	5.632	5.687	5.702	5.686	5.669	5.725	5.738	5.686	5.688	5.701	5.698	5.685	5.702	5.672	5.704				
4	5.604	5.661	5.701	5.688	5.677	5.703	5.753	5.688	5.708	5.708	5.696	5.693	5.688	5.696	5.713				
5	5.609	5.706	5.704	5.688	5.674	5.708	5.74	5.701	5.704	5.696	5.678	5.695	5.677	5.703	5.708				
6	5.621	5.647	5.72	5.699	5.667	5.699	5.756	5.7	5.696	5.688	5.685	5.691	5.698	5.675	5.702				
7	5.632	5.693	5.703	5.688	5.68	5.701	5.757	5.694	5.692	5.681	5.691	5.693	5.686	5.683	5.729				
8	5.672	5.64	5.69	5.712	5.683	5.704	5.794	5.706	5.701	5.687	5.713	5.68	5.709	5.695	5.693				
9	5.531	5.618	5.711	5.685	5.705	5.714	5.695	5.691	5.714	5.698	5.701	5.686	5.698	5.686	5.704				
10	5.598	5.632	5.723	5.695	5.705	5.71	5.685	5.702	5.708	5.69	5.693	5.691	5.673	5.672	5.734				
Average:	5.6036	5.666	5.7051	5.6925	5.6817	5.7095	5.7361	5.695	5.7009	5.6954	5.6936	5.687	5.6915	5.6851	5.707				
STDEV:	0.031465	0.031591	0.010734	0.008759	0.013458	0.00637	0.032824	0.007149	0.009814	0.009663	0.009663	0.007318	0.011048	0.010546	0.014636				
Test Conditions																			
Temperature: -40 to + 85°C																			
Humidity: 69 to 71% @ 25°C																			
Test Performed by:																			
Agoston Agoston																			
Date: 11-05-96																			
Number of pages: 1																			

Table A2 HYPERLABS' Variability Test Results																		
		Reliability Test (Distance to Water Level in Meters)																
Time		10:00 AM	11:30 AM	1:30 PM	2:00 PM	2:30	3:30 PM	5:00 PM	6:00 PM	8:00 PM	9:00 PM	10:00 PM	11:00 PM	12:00 PM	1:00 AM	2:00 AM	4:00 AM	10:00 AM
Measurement																		
1	6.957	5.869	5.861	5.859	5.864	5.867	5.875	5.879	5.867	5.867	5.87	5.869	5.864	5.852	5.854	5.852	5.856	5.863
2	5.845	5.869	5.856	5.862	5.869	5.869	5.864	5.864	5.864	5.853	5.86	5.856	5.869	5.861	5.86	5.854	5.862	5.849
3	5.862	5.878	5.861	5.864	5.855	5.856	5.864	5.869	5.869	5.855	5.878	5.873	5.856	5.85	5.86	5.841	5.864	5.854
4	5.865	5.872	5.864	5.865	5.865	5.859	5.845	5.863	5.871	5.859	5.863	5.861	5.859	5.866	5.846	5.846	5.851	5.839
5	5.867	5.872	5.865	5.866	5.866	5.86	5.864	5.851	5.858	5.861	5.867	5.847	5.861	5.853	5.849	5.848	5.854	5.856
6	5.869	5.859	5.867	5.869	5.869	5.863	5.863	5.855	5.86	5.862	5.868	5.849	5.845	5.855	5.845	5.848	5.853	5.843
7	5.865	5.862	5.868	6	5.862	5.866	5.866	5.859	5.861	5.864	5.852	5.852	5.848	5.857	5.851	5.851	5.856	5.845
8	5.865	5.864	5.866	5.857	5.847	5.851	5.872	5.872	5.867	5.867	5.853	5.853	5.85	5.858	5.854	5.849	5.858	5.845
9	5.871	5.865	5.866	5.859	5.848	5.848	5.853	5.872	5.858	5.863	5.852	5.853	5.85	5.859	5.856	5.851	5.859	5.847
10	5.855	5.866	5.868	5.858	5.858	5.85	5.853	5.872	5.862	5.867	5.854	5.854	5.848	5.861	5.858	5.855	5.861	5.847
Average:	5.8621	5.8676	5.8642	5.863	5.8577	5.8587	5.8647	5.8654	5.8618	5.8617	5.8617	5.8567	5.855	5.8572	5.8533	5.8495	5.8574	5.8488
STDEV:	0.007781	0.005562	0.003824	0.004807	0.007424	0.008125	0.008056	0.007027	0.00494	0.009007	0.008473	0.008014	0.005438	0.004089	0.004169	0.007036		
Test Conditions:							Average:	5.859109										
Temperature: 72 to 80°F																		
Humidity: 69 to 71%							STDEV:	0.005424										
Test Performed by:																		
Agoston Agoston																		
Date: 10-07-96 and 10-08-96																		
Number of pages: 1																		

Appendix B

Well Drilling Logs

DRILLING LOG		DIVISION		INSTALLATION		SHEET 1 OF 4 SHEETS	
1. PROJECT Waterways Experiment Station				10. SIZE AND TYPE OF BIT			
2. LOCATION (Characteristics or Station) 855995.0000 337320.0000				11. DATUM FOR ELEVATION SHOWING (or USL)			
3. DRILLING AGENCY				12. MANUFACTURER'S DESIGNATION OF DRILL			
4. HOLE NO. (As shown on drawing title and file number) : 3396-V-1				13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN : : DISTURBED : : UNDISTURBED			
5. NAME OF DRILLER				14. TOTAL NUMBER CORE BOXES			
6. DIRECTION OF HOLE <input type="checkbox"/> VERTICAL <input type="checkbox"/> INCLINED _____ DEG. FROM VERT.				15. ELEVATION GROUND WATER			
7. THICKNESS OF OVERBURDEN				16. DATE HOLE : STARTED 3/21/1985 COMPLETED 3/21/1985			
8. DEPTH DRILLED INTO ROCK				17. ELEVATION TOP OF HOLE 193.00			
9. TOTAL DEPTH OF HOLE 301.00				18. TOTAL CORE RECOVERY FOR BORING %			
19. SIGNATURE OF INSPECTOR							

ELEVATION ft	DEPTH ft	LOGNO	CLASSIFICATION OF MATERIALS (Description)	X CORE RECOV- ERY %	BOX OR SAMPLE NO. 1	REMARKS (Drilling fluid, water loss, depth of weathering, etc., if significant)
	5		Lean, sandy, silty clay, med plasticity CL			
	10		Silt, very fine sand, clayey fine sand ML			
	15		Lean, sandy, silty clay, med plasticity CL			
	20		Silt, very fine sand, clayey fine sand ML			
	25					
	30					
	35					
	40					
	45					

ENG FORM 1836 PREVIOUS EDITIONS ARE OBSOLETE. MAR 71	PROJECT _____ HOLE NO. _____
---------------------------------------------------------	------------------------------

DRILLING LOG (Cont Sheet)		ELEVATION TOP OF HOLE 193.00		Hole No. 3396-V-1	
PROJECT Waterways Experiment Station			INSTALLATION		SHEET 2 OF 4 SHEETS
ELEVATION +	DEPTH +	LEGEND +	CLASSIFICATION OF MATERIALS (Description) +	% CORE RECOVERY +	BOX OR SAMPLE NO. +
			REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) +		
	55	[Diagonal Hatching]	Lean, sandy, silty clay, med plasticity CL		
	60				
	65				
	70				
	75	[Diagonal Hatching]	Clayey sand, sand-silt mixtures S		
	80		Lean, sandy, silty clay, med plasticity CL		
	85	[Diagonal Hatching]	Fat, inorganic clay of hi plasticity CH		
	90				
	95				
	100				
	105	[Diagonal Hatching]	Clayey sand, sand-silt mixtures S		
	110				
	115	[Diagonal Hatching]	Fat, inorganic clay of hi plasticity CH		
	120				
	125				
	130				
	135	[Brick Pattern]	Limestone LIM		
	140	[Diagonal Hatching]	Lean, sandy, silty clay, med plasticity CL		
	145				
	150	[Brick Pattern]	Limestone LIM		
	155	[Brick Pattern]			
	160				
	165	[Diagonal Hatching]	Lean, sandy, silty clay, med plasticity CL		
		[Diagonal Hatching]	Silty sand,		

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PROJECT _____ HOLE NO. _____

DRILLING LOG (Cont Sheet)			ELEVATION TOP OF HOLE 193.00		Hole No. 3396-V-1	
PROJECT Waterways Experiment Station			INSTALLATION		SHEET 3 OF 4 SHEETS	
ELEVATION +	DEPTH +	LEGEND +	CLASSIFICATION OF MATERIALS (Description)	% CORE RECOVERY +	BOX OR SAMPLE NO. +	REMARKS (Drilling time, water level, depth of weathering, etc., if significant)
			sand-silt mixtures S M			
175						
180						
185						
190			Fat, inorganic clay of hi plasticity CH			
195						
200						
205						
210						
215						
220						
225						
230			Silty sand, sand-silt mixtures S M			
235						
240						
245			Fat, inorganic clay of hi plasticity CH			
250						
255			Silty sand, sand-silt mixtures S M			
260						
265			Lean, sandy, silty clay, med plasticity CL			
270						
275						
280						
285						

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PROJECT _____

HOLE NO. _____

DRILLING LOG (Cont Sheet)			ELEVATION TOP OF HOLE 193.00		Hole No. 3396-V-1	
PROJECT Waterways Experiment Station			INSTALLATION		SHEET 4 OF 4 SHEETS	
ELEVATION +	DEPTH +	LEGEND +	CLASSIFICATION OF MATERIALS (Description) +	% CORE RECOVERY +	BOX OR SAMPLE NO. +	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) +
	295		Fat, inorganic clay of high plasticity CH			
	300					
	305					
	310					
	315					
	320					
	325					
	330					
	335					
	340					
	345					
	350					
	355					
	360					
	365					
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	375					
	380					
	385					
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	395					
	400					
	405					

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PROJECT _____

HOLE NO. _____

Appendix C

Summary of Field Evaluation Data

Table C1
Summary of Field Evaluation Data

	Date C	TDR Water-Level Elevations B				M-Scope Water-Level Elevations	Difference Between Average TDR & M-Scope
		High	Low	Spread	Average		
2	2 Apr '96	94.427	94.332	0.095	94.382	94.395	-0.013
3	3 Apr '96	94.405	94.366	0.039	94.387	94.407	-0.020
4	4 Apr '96	94.361	94.345	0.016	94.352	94.404	-0.052
5	5 Apr '96	94.434	94.422	0.012	94.428	94.435	-0.007
8	8 Apr '96	94.384	94.347	0.037	94.367	94.395	-0.028
12	12 Apr '96	94.296	94.294	0.002	94.295	94.335	-0.040
15	15 Apr '96	94.425	94.419	0.006	94.422	94.432	-0.010
18	18 Apr '96	94.447	94.431	0.016	94.439	94.477	-0.038
19	19 Apr '96	94.426	94.423	0.003	94.424	94.453	-0.029
26	26 Apr '96	94.716	94.704	0.012	94.711	94.749	-0.033
32	2 May '96	95.042	95.033	0.009	95.066	95.066	-0.028
43	13 May '96	94.503	94.494	0.009	94.499	94.532	-0.033
51	21 May '96	94.232	94.225	0.007	94.229	94.301	-0.072
68	7 Jun '96	94.135	94.123	0.012	94.129	94.148	-0.019
86	25 Jun '96	93.936	93.927	0.009	93.932	93.978	-0.046
100	9 Jul '96	93.637	93.630	0.007	93.635	93.694	-0.059
207	24 Oct '96	92.892	92.885	0.007	92.889	92.819	+0.070
211	29 Oct '96	93.105	93.100	0.005	93.103	93.054	+0.049
			Aug	0.017		Aug	-0.033 +0.060

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